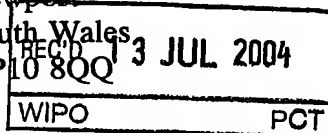




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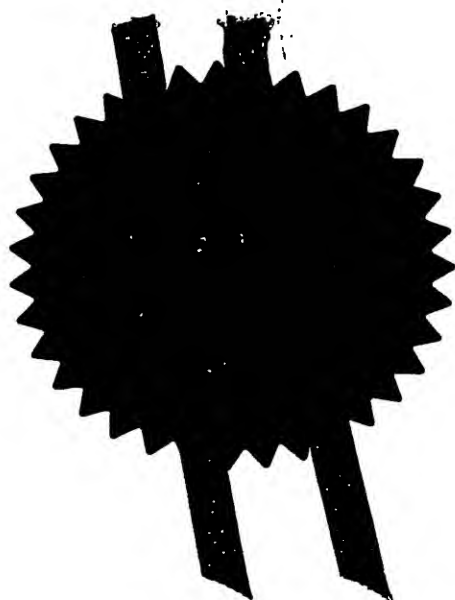
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SP2022 Jg-3141-PCT.

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0323663.5

## 3. Full name, address and postcode of the or of each applicant (underline all surnames)

Southampton Photonics Ltd  
Phi House  
Enterprise Road  
Chilworth Science Park  
Southampton  
SO16 7NS

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

UK

07894330002

## 4. Title of the invention

Apparatus for providing optical Radiation

## 5. Name of your agent (if you have one)

"Address for service" in the United Kingdom  
to which all correspondence should be sent  
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GRAHAM JONES & COMPANY  
77 BLACKWATER ROAD,  
BLACKWATER,  
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MALCOLM VARNHAM

02380

765617

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- 1 -

## **Apparatus for Providing Optical Radiation**

### **Field of Invention**

This invention relates to an apparatus for providing optical radiation. The invention can take various forms, for example a laser, a Q-switched fibre laser, a master oscillator power amplifier, or a laser that contains a frequency converter. The invention has application for materials processing.

### **Background to the Invention**

Pulsed NdYAG lasers are widely used in industrial processes such as welding, cutting and marking. Care has to be taken in these processes to ensure that the plasmas generated by the laser does not interfere with the incoming laser pulses. The relatively low pulse repetition rates (6kHz) at high peak powers that are achievable in a NdYAG laser have led to their wide application in laser machining.

Fibre lasers are increasingly being used for materials processing applications such as welding, cutting and marking. Their advantages include high efficiency, robustness and high beam quality. Examples include femtosecond lasers for multiphoton processing such as the imaging of biological tissues, Q-switched lasers for machining applications, and high-power continuous-wave lasers. Their disadvantage is their relatively low energy storage capacity as compared to NdYAG lasers.

In many applications, fibre lasers need to compete with the more mature diode pumped solid state lasers. In order to do so, much greater optical powers need to be achieved, with high reliability and lower cost.

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Fibre lasers are typically longer than diode-pumped solid state lasers, and this leads to non-linear limitations such as Raman scattering becoming problematical. It would be advantageous to have fibre lasers that are shorter.

Fibre lasers are typically pumped with diode lasers in bar or stack form. The output from bars and stacks is not ideally matched to the geometry of fibre lasers, leading to a loss in brightness, and thus the need to increase the length of cladding pumped fibre lasers in order to obtain the necessary absorption and output energy.

An aim of the present invention is to provide an apparatus for providing optical radiation that reduces the above aforementioned problems.

#### **Summary of the Invention**

According to a non-limiting embodiment of the present invention, there is provided apparatus for providing optical radiation, which apparatus comprises a pump source for providing pump radiation, and a brightness converter, the apparatus being characterised in that the brightness converter is substantially rigid along at least a portion of its length.

The brightness converter may comprise a core, a first cladding, rare earth dopant, a first end, a second end, and a tapered region located between the first end and the second end, the apparatus being characterised in that the cross-sectional area of the first end is greater than the cross-sectional area of the second end, and the brightness converter is substantially rigid between the first end and the tapered region.

The apparatus is particularly useful for increasing the brightness of the pump radiation via absorption into the rare earth dopant and wavelength conversion into modes guided by the core.

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The pump radiation may be coupled from the pump source into the brightness converter using a coupling means. The coupling means may be a lens such as a cylindrical lens.

The apparatus may comprise a first reflector to reflect optical radiation emerging from the first end. The apparatus may also comprise a second reflector.

The pump source may comprise at least one laser diode, laser diode bar, laser diode stack, or a laser diode mini-bar stack. Alternatively or additionally, the pump source may include a solid-state laser, a gas laser, an arc lamp, or a flash lamp.

The apparatus may comprise a plurality of pump sources and a combining means to combine the pump radiation emitted by the pump sources. The combining means may comprise a beam splitter, a reflector, a polarisation beam combiner, a beam shaper, a wavelength division multiplexer, or a plurality of optical fibres in optical contact along at least a portion of their length.

The brightness converter may have multiple cores, or a single core. The brightness converter may be circular or non-circular. The brightness converter may have a cross-section that is rectangular, is a regular or irregular shaped polygon, or is D-shaped.

The brightness converter may comprise rare-earth dopant disposed in the core and/or the first cladding. The rare earth doping may be selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and Dysprosium, or is Erbium codoped with Ytterbium, or is Neodymium codoped with Ytterbium.

The brightness converter may comprise a second cladding.

The apparatus may comprise a waveguide that is pumped by the brightness converter. The brightness converter may be doped with neodymium and/or

ytterbium. The waveguide may be doped with ytterbium, erbium, or erbium co-doped with ytterbium.

The brightness converter may be defined by a width. The width may be in the range 0.1mm to 100mm. The width may be in the range 0.2mm to 25mm. Preferably the width is in the range 5mm to 15mm.

The brightness converter may be defined by a breadth. The breadth may be in the range 0.1mm to 100mm. The breadth may be in the range 0.2mm to 25mm. Preferably the breadth is in the range 2mm to 15mm.

The brightness converter may be defined by a length. The length may be in the range 1mm to 2000mm. The length may be in the range 10mm to 200mm. Preferably the length is in the range 10mm to 50mm.

The brightness converter can be formed from an optical fibre preform. The preform can be made from silica, silicic, phosphate or phosphatic glasses. The preform may contain longitudinally extended holes. The preform may include stress rods.

The apparatus may be in the form of a laser, a Q-switched fibre laser, a master oscillator power amplifier, or a laser that contains a frequency converter.

#### **Brief Description of the Drawings**

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 shows an apparatus for providing optical radiation according to the present invention;

Figure 2 shows an apparatus comprising a plurality of pump sources;

Figures 3 to 5 show examples of brightness converters;

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Figure 6 shows an apparatus in which the brightness converter has been drawn down to a fibre;

Figure 7 shows an apparatus comprising a waveguide;

Figure 8 shows an apparatus comprising an intermediate fibre;

Figure 9 shows an apparatus in the form of a Q-switched laser comprising a Q-switch;

Figure 10 shows a cross-section of the brightness converter of Figure 9;

Figure 11 shows apparatus in the form of a master oscillator power amplifier;

Figure 12 shows apparatus in the form of a master oscillator power amplifier (MOPA), which utilizes the brightness converter to pump a waveguide;

Figure 13 shows apparatus in the form of a laser that comprises a frequency converter within the cavity;

Figure 14 shows an apparatus in which a plurality of pump sources have been combined by a plurality of optical fibres in a common coating; and

Figure 15 shows a cross section of the optical fibres in a common coating described with reference to Figure 14.



### Detailed Description of Preferred Embodiments of the Invention

With reference to Figure 1, there is provided apparatus for providing optical radiation 10, which apparatus comprises a pump source 1 for providing pump radiation 2, and a brightness converter 3, the apparatus being characterised in that the brightness converter 3 is substantially rigid along at least a portion of its length.

The brightness converter 3 may comprise a core 4, a first cladding 31, rare earth dopant 5, a first end 6, a second end 7, and a tapered region 8 located between the first end 6 and the second end 7, the apparatus being characterised in that the cross-sectional area of the first end 6 is greater than the cross-sectional area of the second end 7, and the brightness converter 3 is substantially rigid between the first end 6 and the tapered region 8.

The apparatus is particularly useful for increasing the brightness of the pump radiation 2 via absorption into the rare earth dopant 5 and wavelength conversion into modes guided by the core 4.

The pump radiation 2 may be coupled from the pump source 1 into the brightness converter 3 using a coupling means 9. The coupling means 9 may be a lens such as a cylindrical lens.

The apparatus may comprise a first reflector 11 to reflect optical radiation 10 emerging from the first end 6. The apparatus may also comprise a second reflector 12. Advantageously, the second reflector 12 can be configured to reflect optical radiation 10 emerging from the second end 7. The first and second reflectors 11, 12 may form a laser cavity 13. Preferably the reflectivity of the first reflector 11 is greater than the reflectivity of the second reflector 12 at the wavelength of the optical radiation 10. The first reflector 11 can be a mirror, a dichroic mirror, a dielectric



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The combining means 21 and/or the coupling means 22 can also include one or more beam shapers such as are described in United States patents 5243619, 5557475, 5825551, 6005717, 6151168, 6229940, 6240116, RE 33722, which patents are hereby incorporated herein.

The combining means 21 can be or can include a wavelength division multiplexer configured to combine the pump radiation 2 from two pump sources 1 having different wavelengths.

Beam combining, interleaving, polarisation multiplexing, and wavelength division multiplexing can be used to couple the pump radiation 2 from two to four, or more, pump sources 1 into the beam combiner 3.

Figures 3, 4 and 5 show examples of the cross-sections at the first end 6 of the beam combiner 3. The brightness converter 3 can have multiple cores 4, or a single core 4. Although the brightness converter 3 can be circular, a non-circular cross-section can provide greater coupling between cladding modes and modes guided in the cores 4 as is described more fully in United States patent 4815079 which is hereby incorporated by reference herein. The brightness converter 3 can have a cross-section that is rectangular, is a regular or irregular shaped polygon, is D-shaped. The refractive index of the core 4 is preferably greater than the refractive index of the first cladding 31. The rare-earth dopant 5 can be disposed in the core 4 and/or the first cladding 31. The rare earth doping 5 may be selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and Dysprosium, or is Erbium codoped with Ytterbium, or is Neodymium codoped with Ytterbium. The brightness converter 3 may include a second cladding 51 as shown with reference to Figure 5. The refractive index of the second cladding 51 is

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preferably lower than the refractive index of the first cladding 31. The second cladding 51 may be a polymer.

Figure 6 shows an apparatus in the form of a laser 60 in which the brightness converter 3 is drawn down to a fibre 61. The second reflector 12 is configured as a fibre Bragg grating 62 written in at least one of the core 4 or first cladding 31. An end cap 63 is shown in order to expand the optical radiation 10 prior to it leaving the fibre 61. This is advantageous to reduce the probability of damage at the fibre / air interface. A heat sink 66 is also shown for removal of heat from the brightness converter 3. The heat sink 66 can be air cooled or water cooled. Preferably the heat sink 66 is configured to provide two dimensional contact with the surface of the brightness converter 3. This can be achieved if the brightness converter 3 contains at least one flat surface as would be provided for example by the cross-sections shown in Figures 3 to 5.

Figure 7 shows an apparatus in the form of a laser 70 in which the laser 60 is used to pump a waveguide 71 that comprises at least one core 75, at least one cladding 76, and a gain medium 77. The gain medium 77 can comprise at least one rare-earth dopant disposed in one or both of the core 75 and cladding 76. The laser 60 can be replaced with the apparatus shown by reference to Figure 1. The waveguide 71 can be core pumped or cladding-pumped. Core and cladding pumped fibre lasers are described further in United States patents 4815079, 6288835 and 6445494, which are hereby incorporated herein by reference. The waveguide 71 is shown coupled to the laser 60 by a splice 72. Alternatively, lenses can be used to couple the laser 60 to the waveguide 71. The waveguide 71 is shown as having a first and second fibre Bragg grating 73, 74 in order to form a laser cavity 78.

Figure 8 shows an apparatus in the form of a laser 80 that comprises an intermediate fibre 81 for transmission of the optical radiation 10 from the laser 60 to the waveguide 71. This is a particularly useful arrangement for use in materials processing applications (such as welding, drilling and cutting) because it allows separation of the pump source 1 from the waveguide 71 which can be located on, or in the vicinity of, a machine tool.

Figure 9 shows an apparatus in the form of a Q-switched laser 90 which comprises a plurality of laser diode modules 91 providing pump radiation 2 in optical fibre bundles 92. The pump radiation 2 from the fibre bundles 92 is imaged onto the brightness converter via the lenses 93, the dichroic mirror 94 and the Q-switch 95. The Q-switch 95 can be an acousto-optic modulator or an electro-optic modulator. The brightness converter 3 is formed from an optical fibre preform that has been necked down in to form the taper 8. The first end 6 preferably includes anti-reflection coating. The second end 7 has a fibre Bragg grating 96 to reflect the laser radiation 10. The fibre bundles 92 can be replaced by individual fibres or lenses.

Figure 10 shows a cross-section 100 of the first end 7 of the brightness converter 3 with the pump radiation 2 from the fibre bundles 92 that have been imaged onto its surface shown as individual spots having a diameter 105. The laser diode module 91 can be a FAP-B-60C-1200-BL Fiber Array Packaged Bar from Coherent, Inc. which can provide 60W continuous wave power at 810nm with a beam diameter of 1.2mm with a numerical aperture of 0.16. Thus 780W of pump radiation can be imaged onto the brightness converter 3 if it has cross-sectional dimensions of width 101 of 10mm and breadth 102 of 5mm. If made using optical fibre preform technology, such a preform can be tapered down by a factor of around 100 (in linear dimensions) thus providing an output fibre having dimensions of 100µm by 50µm.

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Referring to Figure 9, with dopant concentrations of rare-earths (such as Neodymium) of a few mole %, and utilizing either large cores 4 or multiple cores 4 (see Figures 3 to 6), good absorption of the pump radiation 2 is possible in lengths 98 of untapered preform 99 of 1cm to 10cm, but preferably 2cm to 5cm. Higher launched power can be achieved by imaging the pump radiation 2 from more laser diode modules 91 onto the first end 7 in smaller spots (with higher numerical apertures).

With practical preform technologies, the width 101 can be in the range 0.1mm to 100mm, the breadth in the range 0.1mm to 100mm, and the length 98 in the range 1mm to 2000mm. The technology lends itself to immediate application with the width 101 in the range 0.2mm to 25mm, breadth 102 in the range 0.2mm to 25mm, and length 99 in the range 10mm to 200mm. Preferably, the width 101 will be in the range 5mm to 15mm, breadth 102 in the range 2mm to 15mm, and length 99 in the range 10mm to 50mm. The ratio of linear cross-sectional dimensions of the first end 6 to the second end 7 can be in the range 2 to 1000, and preferably in the range 10 to 250. By width 101 and breadth 102, it is meant two representative cross-sectional measures across the cross-section 100. Note that the cross-section 100 can be rectangular, circular, square, D-shaped, or other regular or irregular shape. The preform can be made from silica, silicic, phosphate or phosphatic glasses. The preform may contain longitudinally extended holes (not shown) along its length as are found in microstructured fibres, or stress rods such as are those used for inducing birefringence.

Figure 11 shows apparatus in the form of a master oscillator power amplifier (MOPA) 110 comprising a seed source 111 and a beam splitter 112. The beam splitter 112 is preferably dichroic. The seed source 111 may be a laser such as a fibre laser, a Q-switched laser, a pulsed laser, a femtosecond laser, or a semiconductor

laser. The MOPA 110 is shown with the seed source 111 providing laser radiation 113 directed at the second end 7. This has the advantage that the brightness converter 3 will be less multi-moded at the second end 7 than the first end 6.

Figure 12 shows apparatus in the form of a master oscillator power amplifier (MOPA) 120, which utilizes the brightness converter 3 to pump the waveguide 71. The brightness converter 3 may be doped with neodymium and/or ytterbium such that low-brightness 810nm radiation is converted into laser radiation 10 having a higher brightness in a wavelength range that is absorbed by ytterbium (for example in the wavelength range 910nm to 1050nm, but preferably from 910nm to 920nm, 975 to 980nm, or 1030nm to 1050nm). The waveguide 71 may be doped with ytterbium that is pumped by the laser radiation 10. This arrangement is advantageous for core-pumping the waveguide 71 because it allows higher output powers to be achieved before reaching non-linear effects.

Figure 13 shows apparatus in the form of a laser 130 that comprises a frequency converter 131 within the cavity 133 formed by the first reflector 11 and the second reflector 12. The frequency converter 131 may be a frequency doubler, a frequency tripler or a frequency quadrupler. The brightness converter 3 may be doped with neodymium and/or ytterbium, the first and second reflectors 11, 12 may be such that they reflect at the fundamental wavelength of the laser 130 (typically from 910nm to 1100nm), and the frequency converter 131 may utilize a crystal such as barium titanate or lithium niobate for the frequency conversion.

Figure 14 shows a plurality of minibar stacks 141 each of which are coupled into optical fibres 3, 142 using lens 143. The lens 143 may comprise a combination of a cylindrical and spherical lens configured to equalise the far field divergence angle of the pump radiation 2 in orthogonal directions and to couple it efficiently into

the optical fibres 142. The optical fibres 3, 142 have a common coating 140 and are in optical contact along at least a portion of their length -- see Figure 15 -- such that pump power launched in optical fibres 142 couple into and pump the brightness converter 3. The optical fibres 142 can be tapered or untapered.

The examples provided in Figures 9 to 15 were based on fibre coupled laser modules 92. The brightness converters 3 described in these examples are also suited for simple coupling to either laser diode bars, laser diode stacks, or laser diode minibar stacks. These can be combined together or used separately, and can be continuous wave or pulsed. Examples are continuous wave laser diode stacks and bars with output powers of 10W to 1kW or more, and laser diode stacks that can instantaneous pulsed powers in excess of 1kW or more. The laser diode stacks or bars can be water cooled and/or air cooled. Minibar stacks may comprise up to 9 diodes per bar and up to 12 bars in a stack. These may supply as much as 200W pump radiation or more.

It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and additional components may be provided to enhance performance. In addition, the invention can be considered to be a laser, a Q-switched fibre laser, a master oscillator power amplifier, or a laser that contains a frequency converter.

The present invention extends to the above-mentioned features taken in isolation or in any combination.



**Claims**

1. Apparatus for providing optical radiation, which apparatus comprises a pump source for providing pump radiation, and a brightness converter, the apparatus being characterised in that the brightness converter is substantially rigid along at least a portion of its length.
2. Apparatus according to claim 1 wherein the brightness converter comprises a core, a first cladding, rare earth dopant, a first end, a second end, and a tapered region located between the first end and the second end, the apparatus being characterised in that the cross-sectional area of the first end is greater than the cross-sectional area of the second end, and the brightness converter is substantially rigid between the first end and the tapered region.
3. Apparatus according to claim 1 or claim 2 wherein the pump radiation is coupled from the pump source into the brightness converter using a coupling means.
4. Apparatus according to claim 3 wherein the coupling means is a lens.
5. Apparatus according to any one of the preceding claims wherein the apparatus comprises a first reflector to reflect optical radiation emerging from the first end.
6. Apparatus according to any one of the preceding claims and including a second reflector.
7. Apparatus according to any one of the preceding claims wherein the pump source comprises at least one laser diode, laser diode bar, laser diode stack, or a  
----- laser diode mini-bar stack. -----
8. Apparatus according to any one of the preceding claims wherein the pump source includes a solid-state laser, a gas laser, an arc lamp, or a flash lamp.

9. Apparatus according to any one of the preceding claims wherein the apparatus comprises a plurality of pump sources and a combining means to combine the pump radiation emitted by the pump sources.
10. Apparatus according to claim 9 wherein the combining means comprises a beam splitter, a reflector, a polarisation beam combiner, a beam shaper, a wavelength division multiplexer, a plurality of optical fibres in optical contact along at least a portion of their length.
11. Apparatus according to any one of the preceding claims wherein the brightness converter contains a plurality of cores.
12. Apparatus according to any one of claims 1 to 10 wherein the brightness converter contains a single core.
13. Apparatus according to any one of the preceding claims wherein the brightness converter is circular.
14. Apparatus according to any one of claims 1 to 12 wherein the brightness converter is non-circular.
15. Apparatus according to any one of the preceding claims wherein the brightness converter comprises rare-earth dopant.
16. Apparatus according to claim 15 wherein the rare earth doping is selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and Dysprosium, or is Erbium codoped with Ytterbium, or is Neodymium codoped with Ytterbium.
17. Apparatus according to any one of the preceding claims wherein the brightness converter comprises a second cladding.

18. Apparatus according to any one of the preceding claims wherein the brightness converter is doped with neodymium and/or ytterbium and the waveguide is doped with ytterbium, erbium, or erbium co-doped with ytterbium.
19. Apparatus according to any one of the preceding claims wherein the brightness converter is defined by a width, and wherein the width is in the range 0.1mm to 100mm.
20. Apparatus according to claim 19 wherein the width is in the range 0.2mm to 25mm.
21. Apparatus according to claim 20 wherein the width is in the range 5mm to 15mm.
22. Apparatus according to any one of the preceding claims wherein the brightness converter is defined by a breadth, and wherein the breadth is in the range 0.1mm to 100mm.
23. Apparatus according to claim 22 wherein the breadth is in the range 0.2mm to 25mm.
24. Apparatus according to claim 23 wherein the breadth is in the range 2mm to 15mm.
25. Apparatus according to any one of the preceding claims wherein the brightness converter is defined by a length, and wherein the length is in the range 1mm to 2000mm.
26. Apparatus according to claim 25 wherein the length is in the range 10mm to 200mm.
27. Apparatus according to claim 26 wherein the length is in the range 10mm to 50mm.

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28. Apparatus according to any one of the preceding claims wherein the brightness converter is formed from an optical fibre preform.
29. Apparatus according to claim 26 wherein the preform is made from silica, silicic, phosphate or phosphatic glass.
30. Apparatus according to claim 28 or claim 29 wherein the preform contains longitudinally extended holes.
31. Apparatus according to claim 30 wherein the preform includes stress rods.
32. Apparatus according to any one of the preceding claims and in the form of a laser, a Q-switched fibre laser, a master oscillator power amplifier, or a laser that contains a frequency converter.
33. Apparatus substantially as herein described with reference to the accompanying drawings.

1 / 5

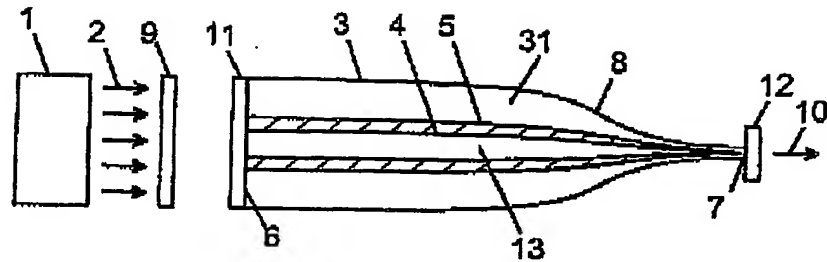


Fig 1

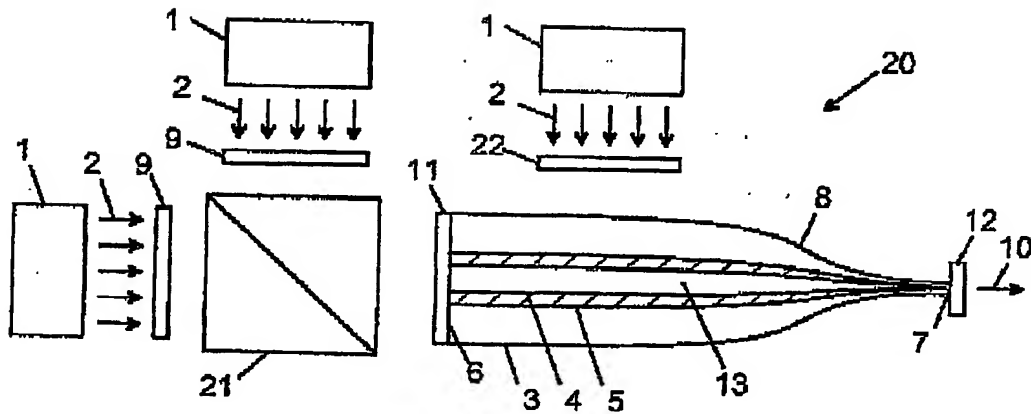


Fig 2

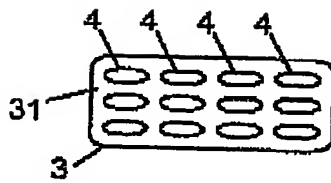


Fig 3

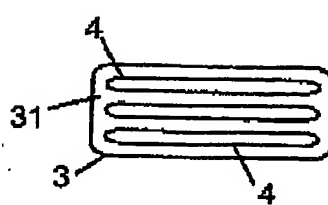


Fig 4

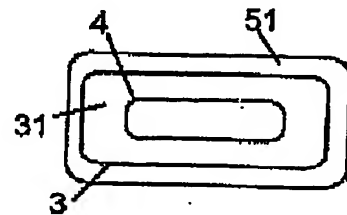


Fig 5

2 / 5

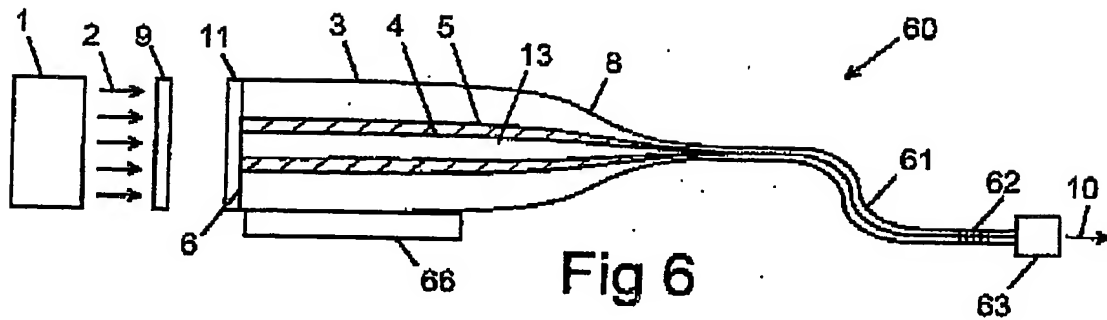


Fig 6

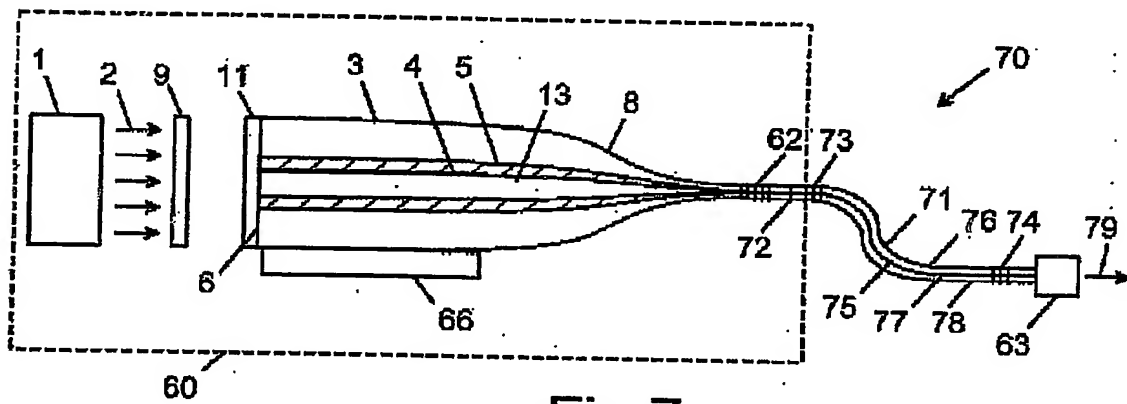


Fig 7

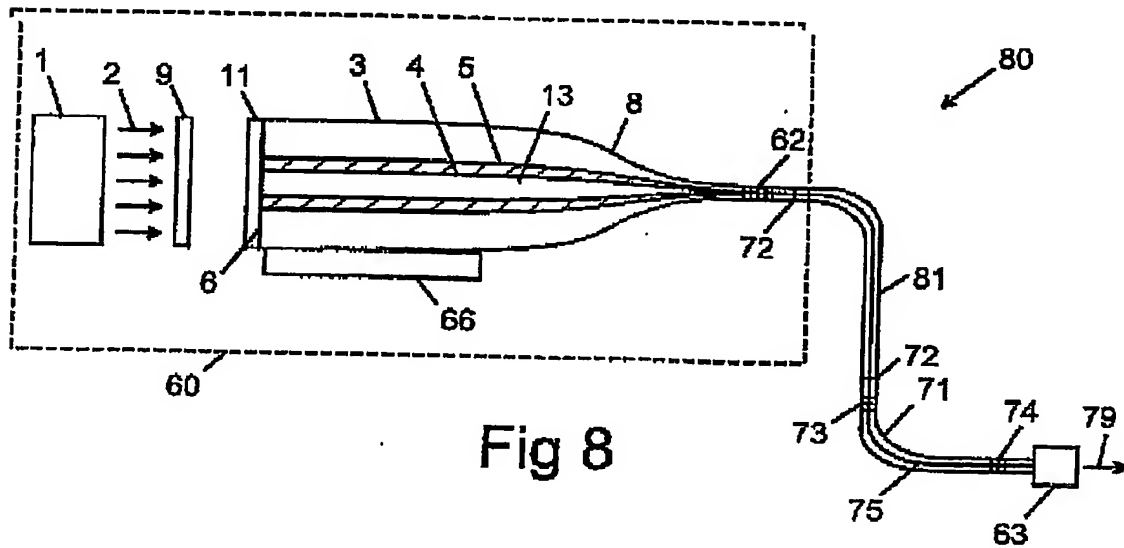


Fig 8

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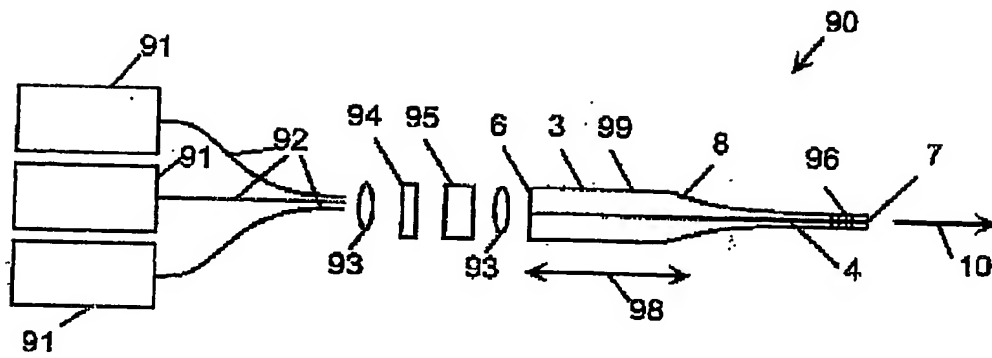


FIG 9

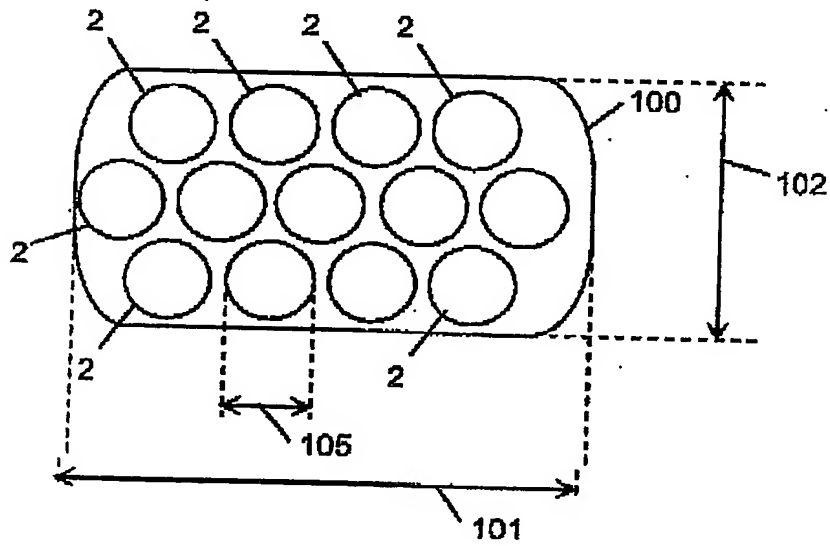


FIG 10

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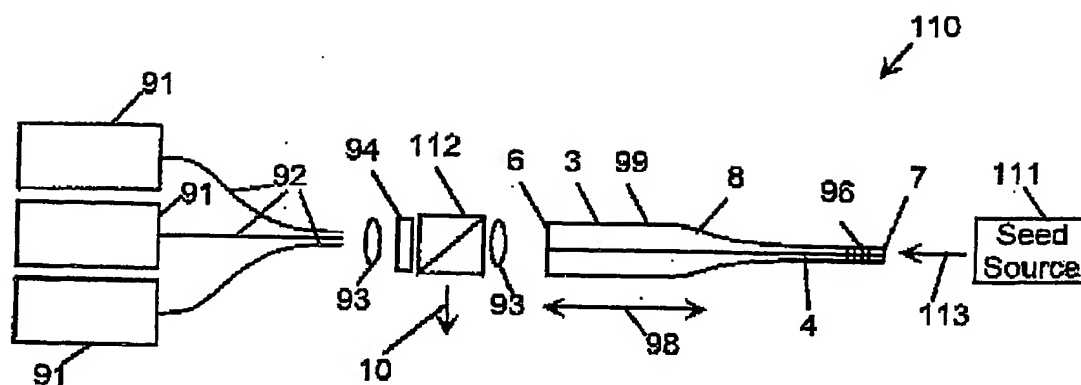


FIG 11

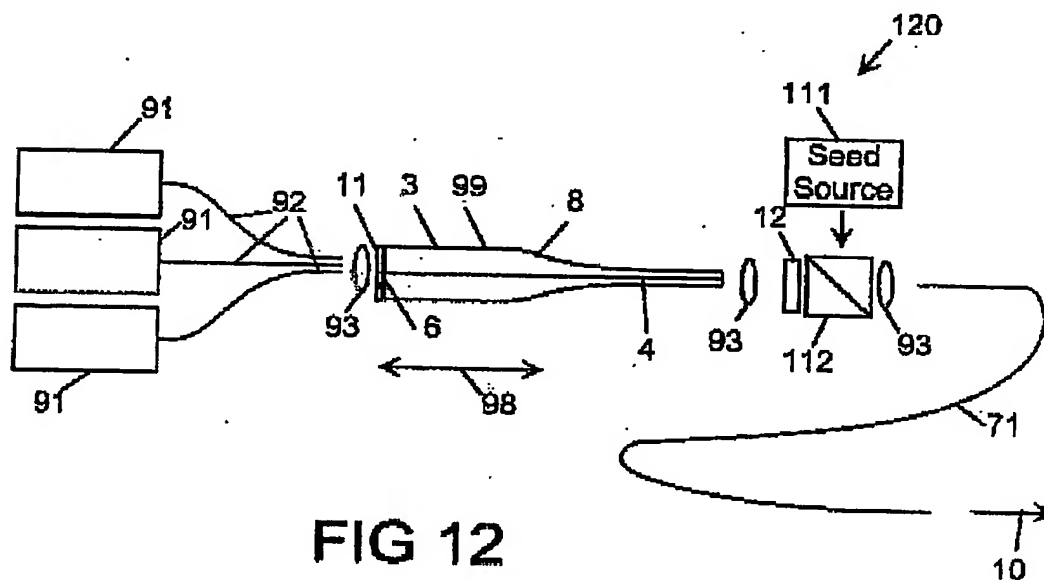


FIG 12



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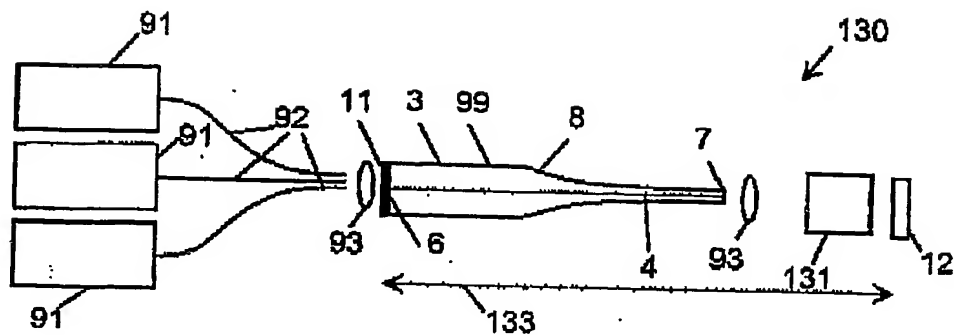


FIG 13

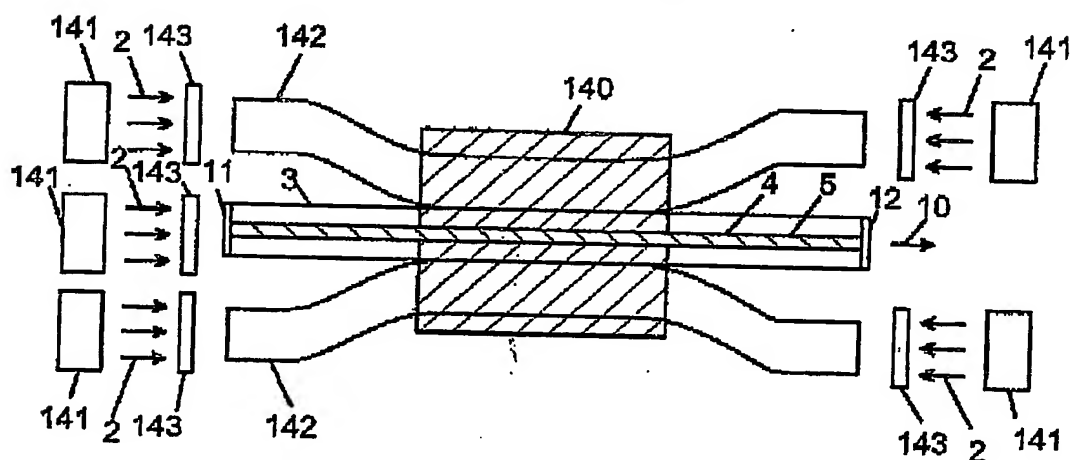


FIG 14

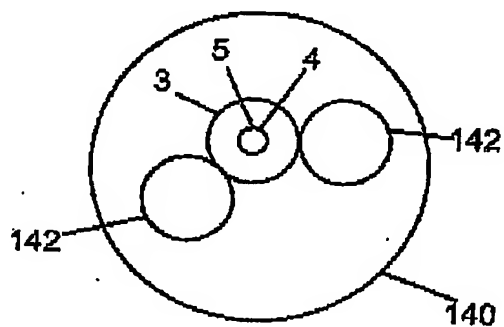


FIG 15

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